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Thermal Control System of the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

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The ECOSystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) is a thermal infrared imaging multispectral scanner science mission. ECOSTRESS is designed and built by the NASA Jet Propulsion Laboratory and will be deployed on the International Space Station (ISS). ECOSTRESS will measure the water loss from growing leaves and the evaporation from the soil by measuring the temperature of plants and will gather data on the health of the agriculture system on Earth. The ISS orbit will allow ECOSTRESS to take observations at different times during each day over the seasons to provide coverage over the contiguous United States. The ECOSTRESS Thermal Control System (TCS) consists of a combination of active and passive components to maintain the ECOSTRESS components within the allowable flight temperature (AFT) limits. The active thermal control systems include mechanical cryocoolers, heaters and a single-phase pumped fluid loop for Instrument and Payload. The focal plane detector is cooled to 65K by a pair of mechanical cryocoolers and a third mechanical cryocooler cools an intermediate cold shield to 130K. The pumped fluid loop transfers the instrument waste heat to JAXA's Japanese Exposed Module External Facility (JEM-EF) provided external fluid loop before rejection to space from the ISS radiators. The passive TCS includes multi-layer and single layer insulations, flexible thermal links and coatings on the radiometer. This paper describes the ECOSTRESS instrument TCS architecture, instrument thermal requirements and key design drivers, the top level thermal design and analysis approach, and reports preliminary test results.

Nomenclature

AFT	=	Allowable Flight Temperature
ATCS	=	Active Thermal Control System
CCE	=	Cryocooler Control Electronics
CCM	=	Cryocooler Control Multiplexer
CEU	=	Central Electronics Unit
FPA	=	Focal Plane Array
FPIE	=	Focal Plane Interface Electronics
HRS	=	Heat Rejection System
ISS	=	International Space Station
JEM-EF	=	Japanese Experiment Module External Facility
MCT	=	Mercury Cadmium Telluride
MLI	=	Multi-Layer Insulation
MSU	=	Mass Storage Unit
PCE	=	Power Conditioning Unit
PTCS	=	Passive Thermal Control System
WEBA	=	Wi-Fi Electronics Box Assembly

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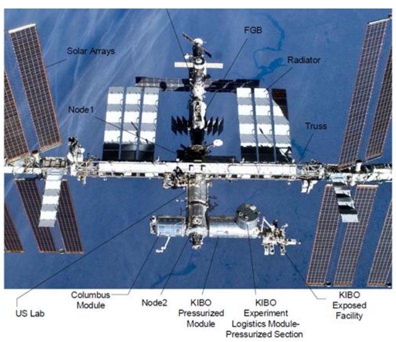
I. Introduction

THE Ecosystem Spaceborne Thermal Radiometer on Space Station (ECOSTRESS) instrument, designed and built for National Aeronautics and Space Administration (NASA) by the Jet Propulsion Laboratory, will be launched in 2018 to the International Space Station (ISS) aboard the SpaceX launch vehicle and will be deployed on the Japanese Experiment Module-External Facility (JEM-EF, also known as KIBO-EF). The JEM-EF is a multipurpose experiment platform where scientific activities including earth observation can be conducted and it can accommodate up to 12 external payloads[1]. The ECOSTRESS instrument is compatible with any of the 12 sites but will be deployed at site 10 (Figure 1). The instrument mission life is twelve months plus one month for in-orbit checkout.



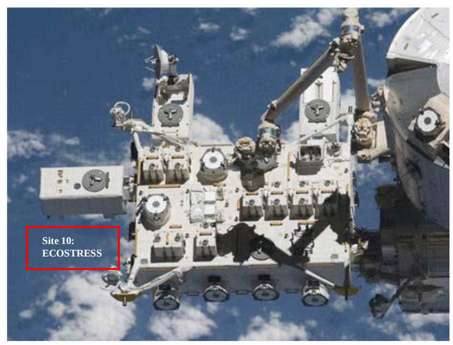


Figure 1. ISS and JEM-EF external payload attachment locations[2]

The ISS provides latitudinal coverage from 51.6° South to 51.6° North. This unique orbit covers 85% of the Earth's surface and allows ECOSTRESS to take observations at different times during each day over the seasons to provide coverage over the contiguous United States (CONUS). The ECOSTRESS instrument will scan the Earth with 38-meters in-track by 69-meters cross-track spatial resolution with a double-sided scan mirror, rotating at 25.4 revolution per minute along with a 65K focal plane with a mercury-cadmium-telluride (MCT) infrared detector array[3]. FPA subsystem has 5 spectral bands in the 8-12.5 micron range and an additional band at 1.6 µm for geolocation and cloud detection. The science objective of the ECOSTRESS mission is to produce a drought indicator product called Evaporative Stress Index (ESI). ESI will indicate whether plants are stressed and that drought is likely to occur in that region.

II. Instrument Description

The ECOSTRESS instrument is divided into three main parts: 1) enclosure structure, 2) radiometer assembly, and 3) support hardware. The enclosure structure is a six-sided box that provides mounting locations for radiometer assembly and support hardware. It is comprised of Cold panel (-Y), Zenith panel (-Z), PIU panel (-X), End panel (+X), Closeout panel (+Y), and NADIR panel (+Z). The NADIR panel is cut away in the middle to accommodate NADIR facing baffle. The ECOSTRESS instrument and its enclosure structure is shown in Figure 2.

The radiometer assembly (shown in Figure 3) consists of the following components: MCT infrared detector array, buffer board, optical elements, yoke assembly, single layer insulation, cold shield, flexible thermal link, blackbody calibration targets, mechanical cryocoolers, NADIR baffle, thermal fluid system (TFS), bulkhead, and contamination enclosure. The contamination enclosure contains the FPA subsystem and its associated thermal and electrical instrumentation. It also provides a structural interface for three cryocooler cold heads and cold head heat exchanger assemblies. The optical elements include primary (M1), secondary (M2), and tertiary (M3) mirrors and they are located in the bulkhead section. The radiometer assembly is mounted on the NADIR panel and is supported by three bipods. These bipods provide thermal isolation between radiometer and +Z panel. The onboard blackbody calibration targets are mounted on the Zenith panel.

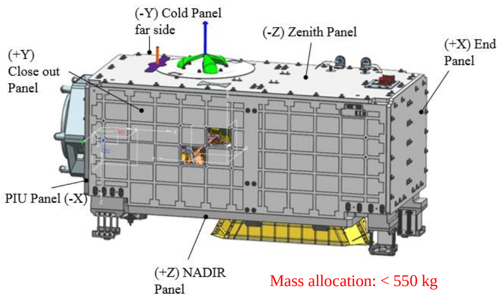


Figure 2. ECOSTRESS instrument and its enclosure structure without the external MLI with beta-cloth outer layer

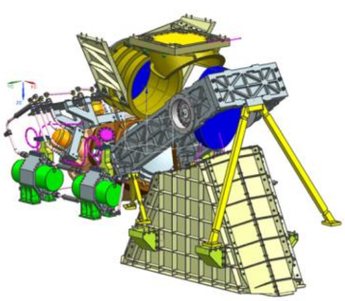


Figure 3. Radiometer Telescope Assembly

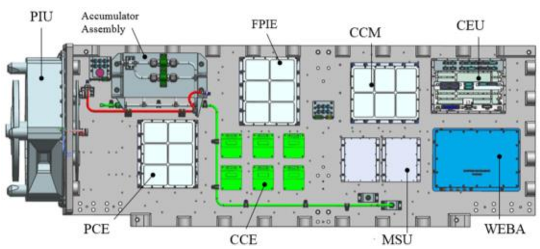


Figure 4. Support Hardware integrated on the –Y enclosure panel

The support hardware includes all subsystems necessary to support instrument operations. The support hardware include Focal Plane Interface Electronics (FPIE), Cryocooler Control Multiplexer (CCM), Cryocooler Control Electronics (CCE), Power Conditioning Electronics (PCE), Mass Storage Unit (MSU), Wi-Fi Electronics Box Assembly (WEBA), Central Electronics Unit (CEU), thermal fluid system tube assembly, and Government Furnished Equipment (GFE). The thermal fluid system tube assembly, high power electronics boxes, and accumulator assembly are mounted on the –Y panel (Figure 4). The payload interface unit (PIU) is a Government Furnished Equipment (GFE) and it provides thermal, mechanical and electrical interface with JEM-EF. All GFE hardware (PIU, FRGF and H-fixtures) and Wi-Fi antennae are externally mounted on the enclosure structures.

III. Thermal Environments

The ISS is maintained in a nearly circular orbit with an average altitude of 400 km at an inclination of 51.6° to Earth's equator with an orbit period of ~90 minutes. ECOSTRESS will be exposed to extreme hot and cold conditions, to solar cycle and solar events, atomic energy, and high energy radiation[4]. Orbit beta angle will vary from -75° to +75° and at higher beta angles, the instrument will be more exposed to Sunlight per orbit. The Torque Equilibrium Attitude (TEA) on ISS will also vary during mission. Table 1 shows the ECOSTRESS thermal environments.

During launch, ISS berthing, and Dragon/JEM-EF transfer, the instrument will be subjected to extreme thermal conditions. Depending on launch vehicle's flight trajectory and its orientation the Sun angle (the angle between direction normal to the Zenith plane and Sun vector) can vary from -90° to +90°. Once Dragon cargo is berthed to ISS, the ISS crew will perform the Dragon and JEM-EF transfer operation. Dragon transfer is a maneuver operation that transfers ECOSTRESS instrument from Dragon cargo to JEM-EF using ISS and JAXA robotic arms. This process can take up to 7 hours and ECOSTRESS is required to survive passively without heater power.

Table 1- Mission Thermal Environment Parameters

	Cold case	Hot case
Solar Flux (W/m^2)	1321	1423
Albedo	0.22	0.35
EARTH IR (W/m^2)	217	273
Beta Angle (degrees]	-75° to +75°	-75° to +75°

IV. Thermal Requirements and Key Design Drivers

The ECOSTRESS thermal design is driven by four key requirements: (1) FPA must be cooled to 65K and maintain thermal stability of <100 mK over 2.4 sec, (2) all subsystems must be maintained within specified operating temperature limits shown in Table 2, (3) the thermal fluid system must comply to the JEM-EF ATCS usage requirements described in the JEM Payload Accommodation Handbook[5], and (4) design must be robust to accommodate changes in Thermal Control System power allocation.

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The ISS requires the ECOSTRESS Payload to be thermally isolated from other ISS and JEM-EF payloads. This led to the use of Multi-Layer Insulation (MLI) and JEM's ATCS cooling loop system for Payload and Instrument heat rejection. Since ECOSTRESS TFS is a pressurized system with fluid circulation provided by the JEM-EF ATCS, it is subject to ISS Fracture Control and JEM-EF ATCS usage requirements. The key parameters that drove the fluid loop design are mass flow rate, pressure drop, and total fluid volume. The JEM-EF ATCS fluid supply temperature ranges from 16°C to 24°C. This relatively high heat sink temperature range, JEM-EF and ISS requirements, and the late reduction in operational power allocation made the thermal design exceptionally challenging. The key thermal control requirements are listed in Table 3.

Table 2. ECOSTRESS Allowable Flight Temperature Limits

ECOSTRESS	**Allowable Flight Temperature**	
Radiometer	Operating	Non-Operating
FPA	-208°C (65K)	-218°C (55K) to 35°C (308K)
Telescope (M1, M2, M3, Scan Mirror)	10°C to 50°C	-15°C to 50°C
Warm Blackbody Target	16°C to 24°C	-15°C to 50°C
Cold Blackbody Target	40°C	-15°C to 50°C
Support Hardware		
CCM	10°C to 50°C	-15°C to 50°C
CCE	10°C to 50°C	-15°C to 50°C
FPIE	10°C to 50°C	-15°C to 50°C
PCE	10°C to 50°C	-15°C to 50°C
CEU	10°C to 50°C	-15°C to 50°C
WEBA	10°C to 50°C	-15°C to 50°C
MSU	10°C to 50°C	-15°C to 50°C
WIFI Antenna	-20°C to 55°C	-20°C to 55°C

Table 3. Key Thermal Requirements

Description	**Requirements**
FPA Operating Temp and Temporal Stability	< 65K, +/- 100 mK over 2.4 sec
Heat Rejection Method	JEM-EF ATCS
Cryocooler Heat Rejection skin temperature	< 40°C
Instrument Cooldown Time	< 24 hrs
Dragon/JEM-EF Transfer Operation Survival Time	7 hrs
Fluid Pressure Drop	55.7 kPa < DP < 58.4 kPa
MLI	Beta Cloth, $e^* < 0.04$
Blackbody Target Temperature and Spatial Gradient	16°C to 24°C (cold)/40°C (warm), <1°C gradient over entire surface
Failure Tolerance	Two fault tolerant
Mass Flow rate	155 kg/hr
Temporary storage	Survive indefinitely at site #12
Cryocooler power allocation	432W
Survival Power	<120W

V. Thermal Architecture

Figure 4 shows the thermal block diagram of ECOSTRESS instrument. The TCS is a combination of active and passive components. The active thermal control systems include mechanical cryocoolers, heaters, and a single-phase pumped fluid loop with circulation provided by the JEM-EF ATCS. The FPA detector is cooled to 65K by a pair of mechanical cryocoolers, and an additional mechanical cryocooler cools an intermediate stage (cold shield) to 130K. The intermediate stage cooling reduces radiative and conductive parasitic loads into the FPA subsystem. Fluid loop

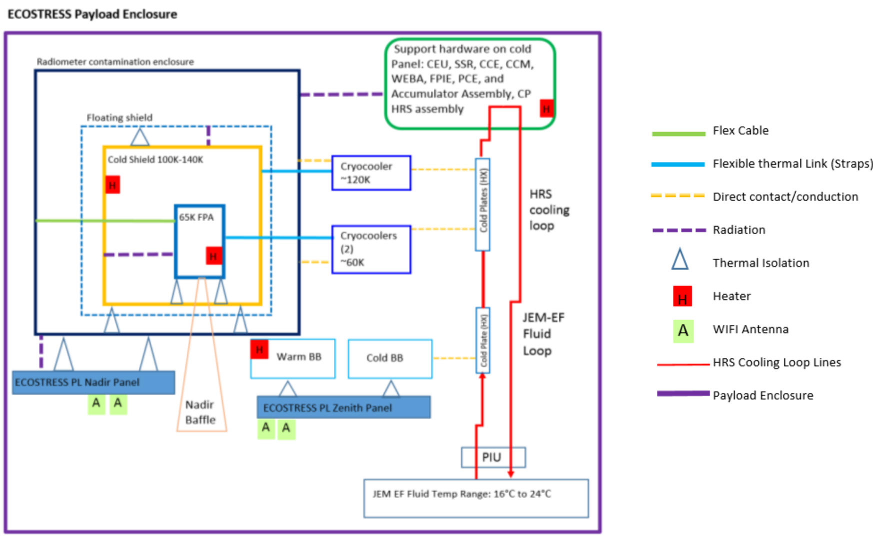

Figure 4. Instrument Thermal Control System (TCS) Architecture

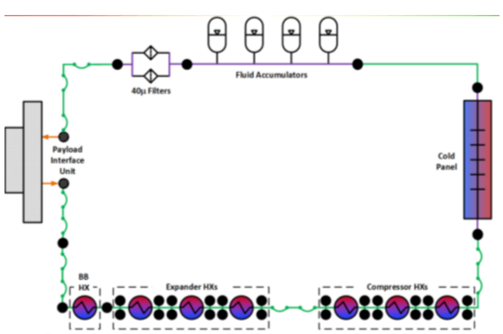

Figure 5. Fluid Loop Diagram

Table 4. MLI Blanket Properties

MLI Properties	
MLI Effective Emittance	$e^* < 0.04$
Solar Absorptivity	$0.31 < a < 0.6$
Emissivity	$0.85 < e < .96$

circulation is provided by the JEM-EF ATCS and manages the 800 W of Payload and Instrument waste heat using Fluoroinert (FC-72) as the working fluid. Figure 5 shows the diagram of ECOSTRESS ATCS fluid loop. The first on-loop component is the cold black body target, which is controlled between 16°C to 24°C during operation. Next, the cryocooler expander and compressor heat exchangers maintain the cryocooler skin reject temperature below 40°C. Lastly, the fluid circulates through a tube heat exchanger assembly that is bonded to –Y Payload panel and cools the high power electronics boxes mounted on the opposite side before exiting the Payload. The passive TCS includes MLI, low emissivity single layer insulation, flexible aluminum thermal links, and surface coatings. Flexible thermal links provide thermal connection between cryocooler cold tip and FPA detector. The enclosure structure is covered in MLI with beta cloth as outer layer. MLI thermal properties are shown in Table 4. The warm blackbody calibration target surface is controlled to 40°C with less than 1°C gradient with flight software and heaters. The MLI and conductive mounts maintain the Wi-Fi antennae to within AFT limits. The survival heaters with thermal switches maintain the support hardware to within non–operating temperature limits. The decontamination heaters on the cold shield and FPA subassembly are used for contamination control.

VI. Cryocooler

The commercially available Thales LPT9310 cryocoolers provide cryogenic cooling for the instrument. LPT9310 coolers can provide 1W to 1.5W of lift at 60K and 6W to 12W of lift at 120K over a wide range of input power and reject temperatures. The cooler is a split pulse tube configuration connected with a custom length transfer line between compressor and expander cold head. The cold head is a coaxial design and has no moving parts. The split design and the absence of moving parts in the expander minimizes the vibration at the detector and cold finger interface. The cooler's MTTF is 90,000 hrs[6].

The LPT9310 cooler is cost-effective and space qualified. In 2013, the LPT9310 cooler underwent a comprehensive flight qualification test program at JPL[7]. Space qualification tests included full functional tests, thermal performance characterization over a wide range of reject temperatures, Thermal Vacuum (TVAC), EMI/EMC, and random vibe. The LPT9310 Cooler's technology readiness level (TRL) is 6. The three coolers are driven and control with the commercially available Cooler Drive Electronics (CDE) model XPCDE4865 electronics from Thales. These electronics will operate in a fairly benign environment; however, to address COTS EEE parts reliability concerns each cooler will have a primary and backup CDE unit. The CCM provides communication and power switching capability between the primary and backup CDE. The Thales XPCDE4865 COTS CCEs have also undergone its own flight qualification tests including TVAC, random vibe, and full functional tests and are at TRL 6.

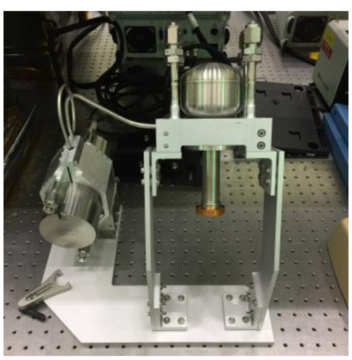

Figure 6. Enhanced Performance High Efficiency LPT9310 cooler shown with MaxQ Cold Plates.

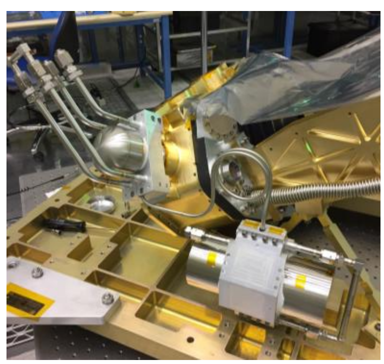

Figure 7. Radiometer Telescope shown with EPHE LPT9310 coolers and non-planar MaxQ Cold Plates.

Early trade studies driven by reduction in TCS power allocation and relatively high fluid loop sink temperature led to the procurement and implementation of enhanced performance high efficiency (EPHE) LPT9310 cooler. The

EPHE LPT9310 (shown in Figure 6) is a modified version of the standard COTS LPT 9310 cooler. The optimization of the cold head with low conductive material significantly improved the cooling performance at 60K. This implementation reduced TCS's power consumption by ~30%. Figure 7 shows the EPHE LPT9310 cooler integrated radiometer assembly.

VII. Cold Plates

The waste heat generated from the three mechanical coolers is removed by custom-built liquid cooled coldplates from MaxQ Technology. These coldplates were specifically designed to minimize the temperature rise between FC-72 fluid and cryocooler rejection surface while meeting the pressure drop and heat transfer requirements. The thermal performance and hydraulic requirements are shown in Table 5. The internal flow geometry with a large surface to volume ratio maximized thermal performance while maintaining an acceptable pressure drop. Advanced friction stir welding manufacturing techniques enabled compact packaging with a non-planar heat transfer interface.

Prior to delivery and integration in the instrument, the coldplates were subjected to proof pressure tests, leakage rate tests, non-destructive evaluations (NDE), and burst pressure qualification tests. Proof pressure tests were performed at 1.5 times the maximum design pressure. Leakage rate tests were performed under vacuum and at 0.75 times the maximum design pressure using helium as the tracer gas. The NDE techniques included radiography for volumetric inspection and fluorescent dye penetrant for surface inspection. Units from each lot were randomly selected, pressurized until burst, and compared against the 2.0X maximum design pressure requirement. All ISS safety and JEM-EF ATCS usage requirements were met. Figure 8 shows the photo of flight compressor liquid cooled cold plates taken prior to flight integration.

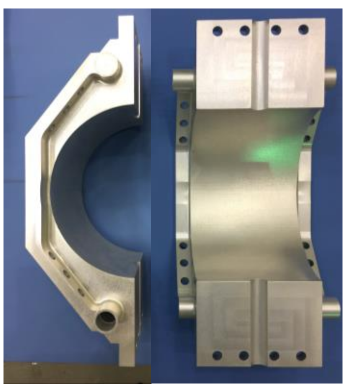

Figure 8. MaxQ's Non-Planar Liquid Cooled Coldplates

Table 5. Coldplate Performance Requirements

Performance requirements at 155 kg/hr:	
Heat Rejection Power	90W per HX
Thermal resistance (from fluid to HX top surface)	<0.09 C/W per HX
Pressure Drop	<0.2 psi per HX
FC-72 Fluid Compatibility	Aluminum 6061-T6
Comply to ISS/JAXA Safety and Fracture Control Requirements	Burst, Proof, NDE tests

VIII. Thermal Instrumentation, Heaters and Thermal Switch

The ECOSTRESS is instrumented with three different types of temperature sensors: 1080 series CERNOX, 670 Diodes, and HRTS 5670 PRTs. CERNOX and Diodes are provided by Lakeshore Inc., and HRTS PRT is provided by Honeywell. The components within the contamination enclosure are instrumented with CERNOX and Diodes and non-cryogenic components are instrumented with the PRTs. Prior to flight integration, PRTs are screened, qualified, and acceptance tested at JPL. The flight temperature sensors are either bonded or mechanically mounted using fasteners. The performance of temperature sensors is verified during radiometer thermal test and during Payload TVAC test.

The heaters on the instrument were all custom-built and acceptance tested to JPL standards. The 700 series thermal switches rated for space application are provided by Honeywell and acceptance tested to NASA S311-641 standards. The thermal switch performance was verified prior to instrument integration.

IX. Thermal Test Setup and Preliminary Test Results

A radiometer assembly thermal performance test was conducted at JPL to verify the thermal design and functionality of the thermal control subsystem. The test configuration is shown in Figure 9. The radiometer system was instrumented with flight and GSE temperature sensors. Operational and decontamination heaters were operated by GSE power supplies. The Yokogawa WT-310 watt meter was used to measure cryocooler input power. During testing, GSE FC-72 flow control unit (FCU) simulated the JEM-EF ATCS circulating loop and provided required flow rate and fluid temperature to the radiometer. The contamination enclosure was under vacuum, the cold and warm blackbody targets were controlled to 24°C and 40°C, respectively. The flight coolers were operated by GSE Thales cryocooler control electronics (CDE7232). The FC-72 fluid temperature was varied from 16°C to 24°C

Figure 10 shows the FPA cool down and warm up temperatures and associated cryocooler input power during one

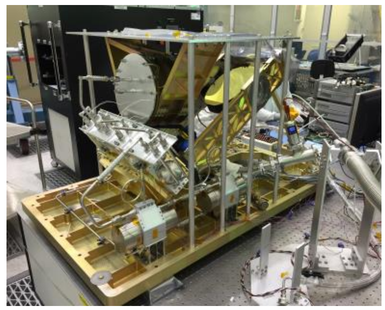

Figure 9. Radiometer Telescope Assembly Thermal Test Configuration

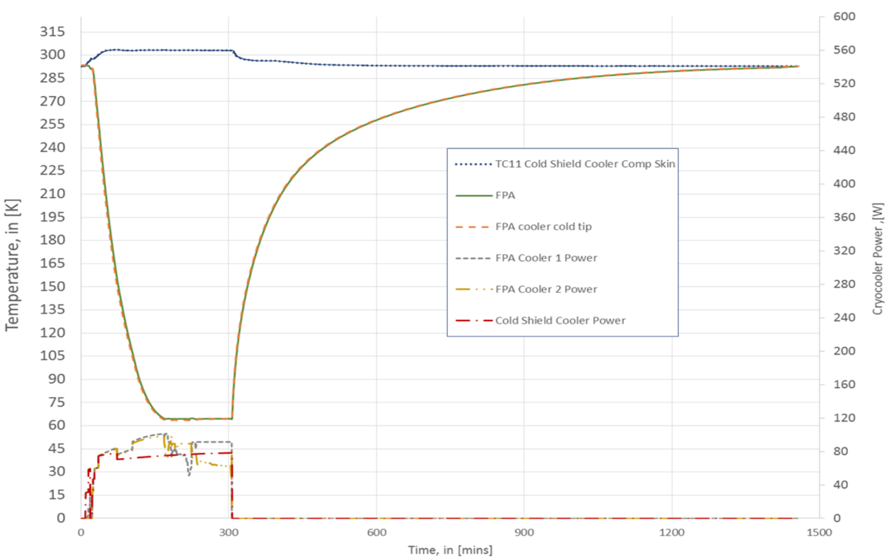

Figure 10. FPA Temperature and Cryocooler Input Power

of the cold alignment tests. The FPA detector achieved 64.7K in approximately 200 minutes. The coolers were operated in open loop control mode during cool down and later switched to closed loop when FPA temperature reached 80K. The measured cryocooler input power (secondary axis) is also shown in Figure 10. The three cryocoolers consumed total of ~250W with FC-72 fluid at 24°C. Because test was conducted on a bench top in ambient environment a portion of waste heat is lost to free convection. This heat loss is measured to be on the order of 40W to 50W. In an actual vacuum environment the cryocooler will consume more power but it is anticipated that this power will still be less than 432W. The calculated cold plate thermal resistance based on the measurement was 0.057°C/W. The maximum gradient on the blackbody target surface was 0.5°C. Thermal balance test was also conducted on the radiometer for thermal model validation and correlation.

X. Summary

A thermal control system has been successfully designed to meet the challenging ECOSTRESS thermal requirements. A combination of active and passive thermal control systems was employed to maintain the components within the AFT limits. The radiometer thermal performance test results were excellent and repeated performance was demonstrated over a range of FC-72 fluid temperatures (16°C to 24°C). The cryocoolers and cold plates operated better than anticipated and no temperature limits were exceeded. The flight temperature sensors and heater operated nominally. The implementation of EPHE cooler and coldplates minimized the TCS power consumption. The system level thermal control system design will be verified in Payload TVAC testing which is planned for summer 2017.

Acknowledgments

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References

[1] Kawasaki, K., "Overview of JEM-EF on ISS," Proceedings of the RIKEN Symposium held 10-11, June 2008 Japan, pp.1-3.
[2] JAXA, "Kibo Exposed Facility User Handbook," Sept 2010.
[3] Jet Propulsion Laboratory ECOSTRESS home page, https://ecostress.jpl.nasa.gov
[4] Finckenor, M. M. and de Groh, K. K., "A Research's Guide to International Space Station," NASA ISS Program Science Publication, NP-2015-03-015-JSC. March 2015.
[5] NASDA, JEM Payload Accommodation Handbook (JPAH) Vol. 3. "Exposed Facility/Payload Standard Interface Control Document, NASDA-ESPC-2563," (NASDA-ESPC-2563 Japanese Version; NASDA-ESPC-2900 English Version
[6] Cryogenic Cooler LPT 9310/17 Specification, Thales Cryogenics, June 17, 2013.
[7] Johnson, D.L., McKinley, I.M., Rodriguez, J.I., Tseng, H., Carroll, B.A., "Characterization Testing Of the Thales LPT9310 Pulse Tube Cooler," *Cryocoolers 18*, Kluwer Academic/Plenum Publishers, New York (2014), pp. 125-133.